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Minijet activity in high E_T jet events at the Tevatron

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ABSTRACT

Gluon bremsstrahlung in scattering events with high transverse momentum jets is expected to increase markedly with the hardness ($\sum E_T$) of the primary event. Within perturbative QCD we estimate a probability of order unity to see additional minijets with $E_T \gtrsim 15$ GeV in "dijet" events with $\sum E_T > 400$ GeV. The veto of such minijets is a promising background rejection tool for the Higgs search at the LHC.

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The study of detailed properties of high transverse energy (E_T) jet events in $p\bar{p}$ collisions at the Tevatron has become an important testing ground for perturbative QCD (pQCD)[1]. At the same time the investigation of hadronization patterns in dijet events with widely separated jets has lead to the discovery of rapidity gaps at the Tevatron [2] and has demonstrated that the color structure of the hard scattering event has dramatic consequences for the angular distribution of produced hadrons at hadron colliders [3, 4, 5]. More precisely it is the t-channel exchange of color singlet quanta which can lead to rapidity gaps. One of the most important members of this class of processes will be weak boson scattering at hadron supercolliders, i.e. the electroweak process $qq \to qqVV$, and, indeed, a rapidity gap trigger had been suggested as a promising Higgs search tool at the SSC [4].

A modified rapidity gap trigger, in terms of minijets of $E_T > 15 - 20$ GeV instead of soft hadrons, was recently suggested for the study of weak boson scattering at the LHC [6]. Due to the high luminosity of the LHC, which leads to multiple pp interactions in a single bunch crossing, the search for rapidity regions without soft hadrons is rendered impractical. Minijets of sufficiently high E_T, however, are unlikely to be produced by multiple interactions. On the theoretical side rapidity gaps are not well described by pQCD which makes predictions about jets rather than individual hadrons. Minijets, on the other hand, can be described by pQCD if the perturbative expansion is taken far enough.

A key component of the minijet veto is the observation that the emission of semihard partons, soft at the level of the hard scattering process but still leading to distinct minijets, becomes quite probable in the very hard QCD background processes to weak boson scattering. A tree level calculation for the QCD W pair background reveals that the production cross sections for WWj and $WWjj$ events become equal when the minimal E_T for which partons are identified as jets is taken to be of order $30 - 40$ GeV [6]. This leads us to expect the emission of multiple minijets with $E_T > 20$ GeV in these background processes. The E_T-scale can be understood qualitatively by noting that the invariant mass of the two W's must be in the 600–1000 GeV range to become a background for a heavy Higgs boson and the presence of an additional forward tagging jet increases the required c.m. energy $\sqrt{\hat{s}}$ into the TeV range. The emission of additional gluons above a transverse momentum $E_T^{\min}$ is suppressed by a factor $f_s \approx \alpha_s \ln\,(\hat{s}/E_T^{\min 2})$ and this factor approaches unity for

$E_T^{\min} = \mathcal{O}(30\text{ GeV})$. Multiple minijet emission at such large E_T's should be observable even in a high luminosity environment and it is the veto of these minijets which should substantially reduce the backgrounds with little effect on the signal rates (due the different color structure and QCD scales of the latter).

The approximate equality of n- and $n+1$-parton cross sections clearly indicates that fixed order pQCD is no longer reliable in this range. One would like to have experimental data on minijet multiplicities, veto probabilities, angular distributions and the like and to then gauge the pQCD calculations for new physics backgrounds in the light of these direct observations. In this letter we suggest that such information can already be obtained in the hardest QCD events available now, namely in hard "dijet" events at the Tevatron.

In the following we consider pQCD predictions for dijet production at the Tevatron in next-to-leading order (NLO), using the NLO Monte Carlo program JETRAD of Giele, Glover and Kosower [7]. MRSD$'_-$ distribution functions [8] are used and the strong coupling constant $\alpha_s(\mu)$ is evaluated at 2-loop order with $\alpha_s(m_Z) = 0.111$. Both the renormalization and the factorization scales are chosen as $\mu = \sum E_T/4$, where $\sum E_T$ is the scalar sum of the parton transverse momenta. The program allows us to make accurate estimates for the two-jet inclusive cross section ($\sigma_{2,\mathrm{incl}}$) at the 1-loop level. In addition, three parton final states are simulated at tree level which allows the study of soft minijet activity at leading order. For the three parton cross section (σ_3) the usual scale ambiguity of tree level calculations arises, which in the present case is exacerbated by the very different scales of the hard event ($\sum E_T = \mathcal{O}$ (500GeV)) as compared to the transverse momentum of the softest parton ($E_{T_3} = \mathcal{O}(20\text{ GeV})$). Truly we are dealing with a 2-scale problem and a rough estimate of the ambiguities is obtained by comparing $\sigma_3(\mu = \sum E_T/4)$ with $\sigma_3(\mu = \sum E_T/4)\cdot\alpha_s(E_{T_3})/\alpha_s(\sum E_T/4)$ *i.e.* by effectively using the softest E_T as the scale for emission of the additional parton. We will refer to these two choices as $\mu_3 = \sum E_T/4$ and $\mu_3 = E_{T_3}$, respectively.

We cluster partons into jets using a D0 style cone algorithm [9]. If two partons are to be clustered into a jet we form the jet momentum as

$$\mathbf{p}_{\mathrm{jet}} = \mathbf{p}_1 + \mathbf{p}_2 , \tag{1}$$

$$E_{T_{\rm jet}} \quad = \quad E_{T_1} + E_{T_2} \ . \tag{2}$$

Each pair of partons is clustered into a temporary jet. Whenever both partons are within a distance

$$\Delta R({\rm jet},{\rm parton}) \equiv \sqrt{(\eta_{\rm jet}-\eta_{\rm parton})^2+(\phi_{\rm jet}-\phi_{\rm parton})^2} < 0.7 \tag{3}$$

of the temporary jet, then these partons are clustered into an actual jet. Since we are dealing with a maximum of three partons in the final state, at most one such recombination of massless partons can occur in our program.

Final (clusters of) partons are then counted as jets if their transverse energy E_T and pseudorapidity η satisfy the conditions

$$E_T > E_T^{\rm min}\,, \qquad\qquad |\eta| < 3.5\ , \tag{4}$$

with, typically, $E_T^{\rm min} = 15$ GeV. We define the $\sum E_T$ of the event as the sum of the E_T's of all observed jets.

In Fig. 1 we show the fraction of 2 jet inclusive events that contain a third jet, for values $E_T^{\rm min} = 15$, 20, and 30 GeV. The 3 jet fraction $f_3 = \sigma_3/\sigma_{2,{\rm incl}}$ is plotted as a function of the $\sum E_T$ of the event and for the two choices of the effective scale governing soft minijet emission. Below ≈ 200 GeV one observes a marked rise of the fraction of three jet events with $\sum E_T$ which then flattens out around $\sum E_T = 300$ GeV and slowly decreases for larger values. This pattern can be understood by considering the phase space, both in E_T and pseudorapidity, which is available to the third parton. By definition, this is the parton with the smallest E_T and hence its allowed range is $E_T^{\rm min} < E_T < \sum E_T/3$. Integration of the partonic cross section $d\hat\sigma \sim dE_T/E_T$ over this range leads to a logarithmic increase of the 3 jet fraction and explains the rise of $\sigma_3/\sigma_{2,{\rm incl}}$ for small $\sum E_T$.

For 2-jet events and, approximately, for 3-jet events with a soft central jet the rapidity difference of the two highest E_T jets and the c.m. energy are related by

$$\sqrt{\hat s} = \sum E_T \cdot \cosh\frac{\eta_1-\eta_2}{2}\ . \tag{5}$$

Due to the rapid decrease of parton luminosity with rising $\hat s$ only small rapidity differences $\eta_1 - \eta_2$ can be reached at high $\sum E_T$. This effect is demonstrated in Fig. 2: the rapidity

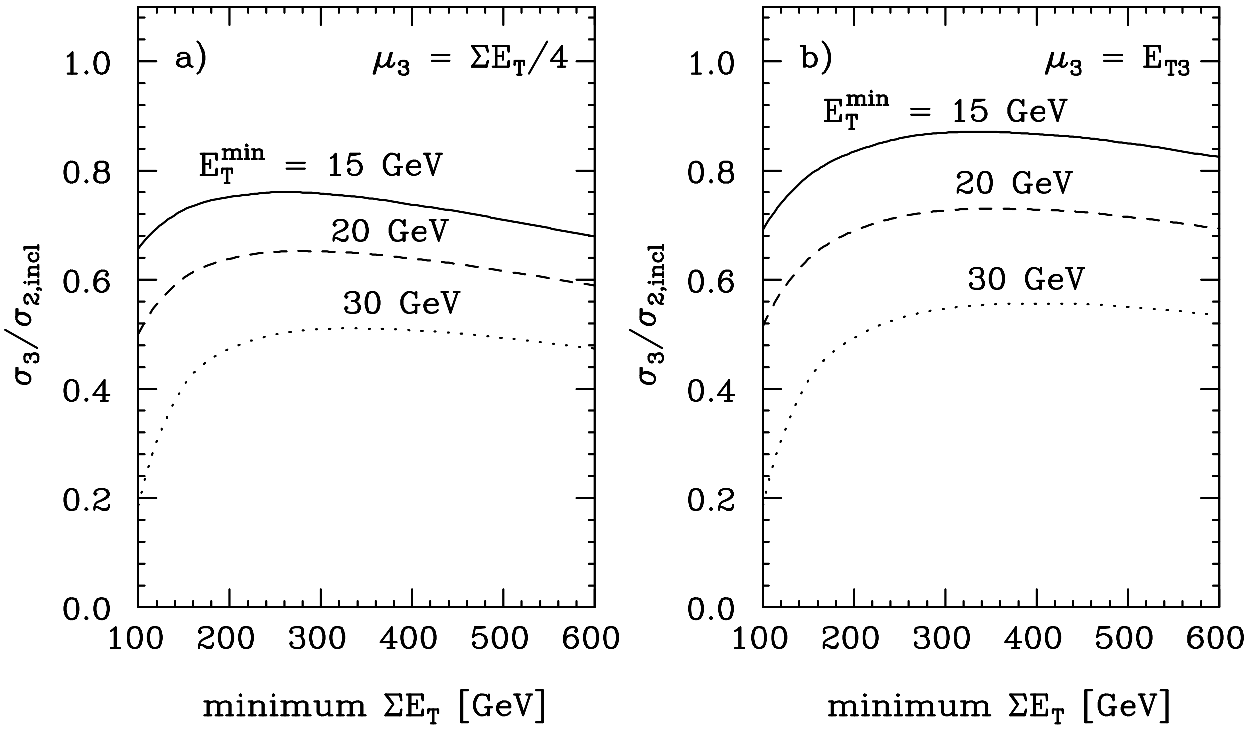

Figure 1: Fraction of 2-jet inclusive events that contain a third jet within the acceptance requirements of Eqs. 3,4. The 3-jet cross section is integrated above a minimal $\sum E_T$ and above minimal transverse energies E_{T_3} of the softest jet of 15 GeV (solid line), 20 GeV (dashed line) and 30 GeV (dotted line). The renormalization scale is set to $\mu = \sum E_T/4$ in part a). Changing the effective coupling constant for soft parton emission in the 3-jet cross section to $\alpha_s(E_{T_3})$ yields the results shown in part b).

distribution in the c.m. frame, $d\sigma/d|\eta_1 - \eta_2|$ becomes narrower with increasing $\sum E_T$. The emission of a third jet well outside the rapidity interval set by the two hardest jets will markedly increase the $\hat{s}$ of the event and hence will suffer from a lower parton luminosity. Thus additional soft jets are predominantly produced in the rapidity range set by the two hard jets and therefore the decrease of the average $|\eta_1 - \eta_2|$ with increasing $\sum E_T$ reduces the phase space for emission of additional jets. This explains the decreasing fraction of three jet events at large $\sum E_T$ which was observed in Fig. 1.

These phase space effects are very process specific. In weak boson scattering events at the LHC, for example, (and backgrounds to these events) the available $\hat{s}$ is largely determined by the forward and backward tagging jets and hence the kinematically favored rapidity range

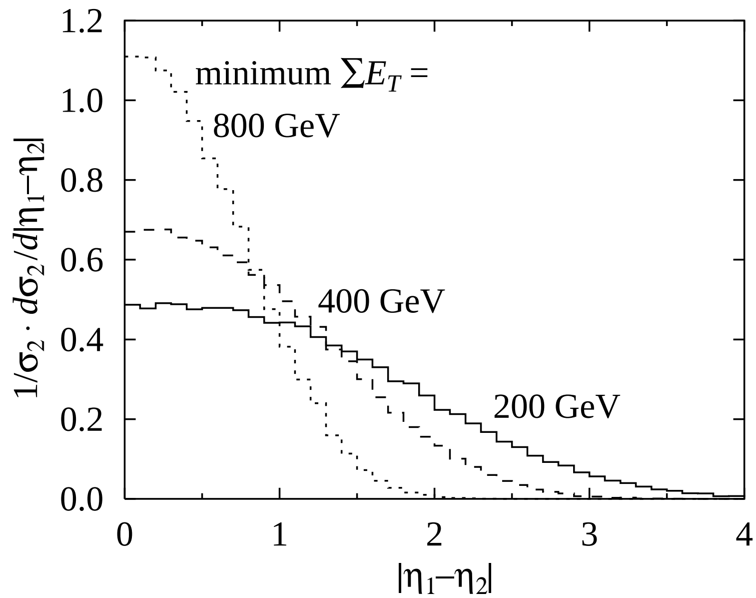

Figure 2: Normalized rapidity distribution $1/\sigma_2 \;\cdot d\sigma_2/d|\eta_1-\eta_2|$ for 2-jet inclusive events at the Tevatron. Shown is the narrowing of the rapidity range $|\eta_1-\eta_2|$ with increasing hardness ($\sum E_T$) of the event.

for minijet emission is much larger than in dijet events at the Tevatron. For a comparison of different processes one would like to eliminate these purely kinematical effects. For jet production at the Tevatron our Monte Carlo studies show that, to good precision, the probability for a 3rd jet to be produced in the η range between the two hardest jets rises linearly with the η-ϕ phase space which is available for that third jet, that is

$$\frac{\sigma_3(\eta_3\in[\eta_1,\eta_2])}{\sigma_{2,\mathrm{incl}}} \sim A_{\mathrm{lego}} \equiv 2\pi|\eta_1-\eta_2| - A_{\mathrm{cone}}\ , \tag{6}$$

where A_{cone} is the part of the lego-plot region between η_1 and η_2 which is covered by the two cones of radius 0.7 about the two hardest jets. We therefore divide out the available phase space A_{lego} and consider the probability density for emission of a third jet in the lego-plot. In Fig. 3 we show the average density

$$\rho_{\mathrm{lego}} = \frac{1}{\sigma_{2,\mathrm{incl}}}\int_{\eta_1}^{\eta_2} d\eta_3 \int_0^{2\pi} d\phi_3\ \frac{1}{A_{\mathrm{lego}}}\ \frac{d^2\sigma_3}{d\eta_3 d\phi_3} \tag{7}$$

for emission of the third, lowest E_T, jet in the interval $[\eta_1,\eta_2]$ set by the two hardest jets. The probability density as a function of the minimal $\sum E_T$ of the event is shown in Fig. 3a, while

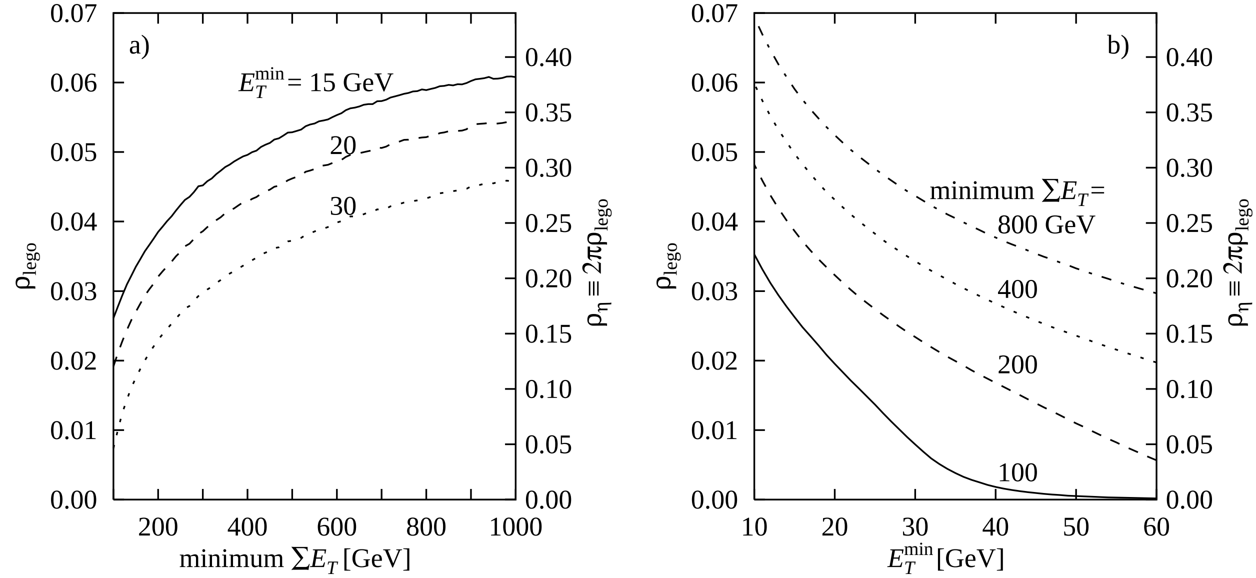

Figure 3: Lego-plot density $\rho_{\rm lego}$ of soft jets between the two hardest jets. Results are shown a) as a function of the minimal $\sum E_T$ and for three values of $E_T^{\rm min}$ and b) as a function of $E_T^{\rm min}$ with $\sum E_T$ as a parameter. The effective coupling constant for soft parton emission in the 3-jet cross section has been set to $\alpha_s(E_{T_3})$. On the r.h.s. the scale is multiplied by a factor 2π to show the approximate density per unit of pseudorapidity.

Fig. 3b depicts the same probability density as a function of $E_T^{\rm min}$, the minimal transverse momentum of the minijet. One now observes a monotonic increase with the hardness of the overall event, $\sum E_T$. It is this increase which is characteristic of the effect of enhanced minijet emission and which allows to distinguish it from backgrounds due to the underlying event. Factorization of the hard event implies that the background from the underlying event, that is minijet emission caused by the interactions between the colored remnants of the original $p\bar{p}$ pair, does not grow as the $\sum E_T$ of the hard event increases. The minijet background from the underlying event may even decrease at very high $\sum E_T$ because less longitudinal momentum is available for the interactions between the $p\bar{p}$ remnants.

For very hard events, $\sum E_T > 400$ GeV say, the minijet emission probability reaches remarkably large values, of order 0.3 per unit of rapidity for minijets of $E_T > 15$ GeV. These large probability densities reflect the approximate saturation of the 2-jet inclusive cross section with 3-jet events which is evident in Fig. 1. Clearly, for hard jet events at

the Tevatron with $\sum E_T \approx 400$ GeV the calculation of jet multiplicities within fixed order pQCD is breaking down for jet thresholds as large as $E_T^{\min} = 30$ GeV. One should expect large probabilities for 4 or 5 jet events as well, but a reliable prediction of these multijet fractions goes beyond the perturbative tools at hand. A leading logarithm parton shower calculation does allow to simulate such events. However, the scale of the logarithms remains uncertain and the multijet rates are again subject to large normalization uncertainties. Experimental input is needed in addition to theoretical considerations. It should be noted that these events are not rare, indeed $\sigma(\sum E_T > 400 \text{ GeV}) \approx 200$ pb. Thus we expect a large sample of high $\sum E_T$ events at the Tevatron which exhibit multiple emission of additional minijets in the $10-30$ GeV E_T range and which can be used to study the characteristics of minijet emission.

Specific questions which should be addressed experimentally are

1. What is the average multiplicity of minijets and how does it change with the $\sum E_T$ of the event?

2. How are minijet multiplicities distributed? The NLO Monte Carlo only allows to generate events with 0 and 1 minijet.

3. Down to which $E_T^{\min}$ can one distinguish minijet activity arising in the hard scattering event from minijets in the underlying event?

4. What is the probability for zero minijet emission in a hard scattering event? How does this probability change with $\sum E_T$? How does it depend on the minimal transverse energy $E_T^{\min}$ which is required for a cluster of hadrons to be identified as a jet?

5. Does the effective coupling, which governs the emission of minijets, depend on the hard scattering scale, the soft scale, or some combination of the two?

The results shown in Fig. 1 can only be considered crude estimates, as can be seen from the differing predictions when changing the scale of soft emission from $\sum E_T/4$ to E_{T_3}. Theoretically this question of scale can be resolved by going to the next order in pQCD, in this case calculating 3 jet production at NLO. Experimental information on this scale is obtained by comparing the rise of the lego-plot density as a function of $\sum E_T$ with the

$\mu_3 = E_{T_3}$ prediction in Fig. 3a. Considering the large uncertainties of our pQCD calculation it is well possible, however, that a relatively large correction factor F is needed to relate the experimental minijet density with the pQCD expectation,

$$\text{Minijet density} = F\, \rho_{\text{lego}} = \frac{F}{\sigma_{2,\text{incl}}} \int_{\eta_1}^{\eta_2} d\eta_3 \int_0^{2\pi} d\phi_3 \, \frac{1}{A_{\text{lego}}} \, \frac{d^2\sigma_3}{d\eta_3 d\phi_3} \,. \tag{8}$$

Measuring the dependence of this correction factor on the kinematics of the hard event ($\sum E_T$ and $|\eta_1 - \eta_2|$) would provide a useful guide for theoretical improvements, which would then help to more reliably predict minijet emission probabilities in hard scattering events at the LHC.

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